Energy Efficient Routing and Self-Configuring Networks

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Cornell Networking Effort – Fall 2001

- Quantifying performance improvement provided by directed diffusion (collaboration with Deborah Estrin).
- Enhancing performance of content-aware networking through more powerful aggregation techniques.
- Developing simulation testbed for experimental verification of the analytical and theoretical results in the above two areas.
- Continued focus on bounded complexity – managing problem difficulty in self-organizing sensor networks.

Modeling Data-Centric Routing

- Optimal Aggregation: The optimum number of transmissions required per datum for a simple data-centric protocol is equal to the number of edges in the minimum Steiner tree - NP complete in general.
- Suboptimal Approaches:
  - Center at Nearest Source
  - Shortest Paths Tree
  - Greedy Incremental Tree
- Performance Measures:
  - Energy Savings
  - Delay
  - Robustness

Energy Savings Due to Data Aggregation

- Theoretical Results: “The Impact of Data Aggregation in Wireless Sensor Networks” by Krishnamachari, Estrin, and Wicker
  - Gains with respect to address-centric clearly lie in aggregation
  - Even simple duplicate-suppression/max/min aggregation functions can provide significant gain.
    - Bounds derived for several cases
    - Experimental results support analysis
  - Source-sink placements and network topology impact performance and complexity of aggregation techniques.
  - Results suggest a tradeoff between energy and delay that could be incorporated into data-centric routing schemes.

Energy Savings Due to Data Aggregation

- Let the fractional energy savings from using data aggregation be $\eta = N_D/N_A$.

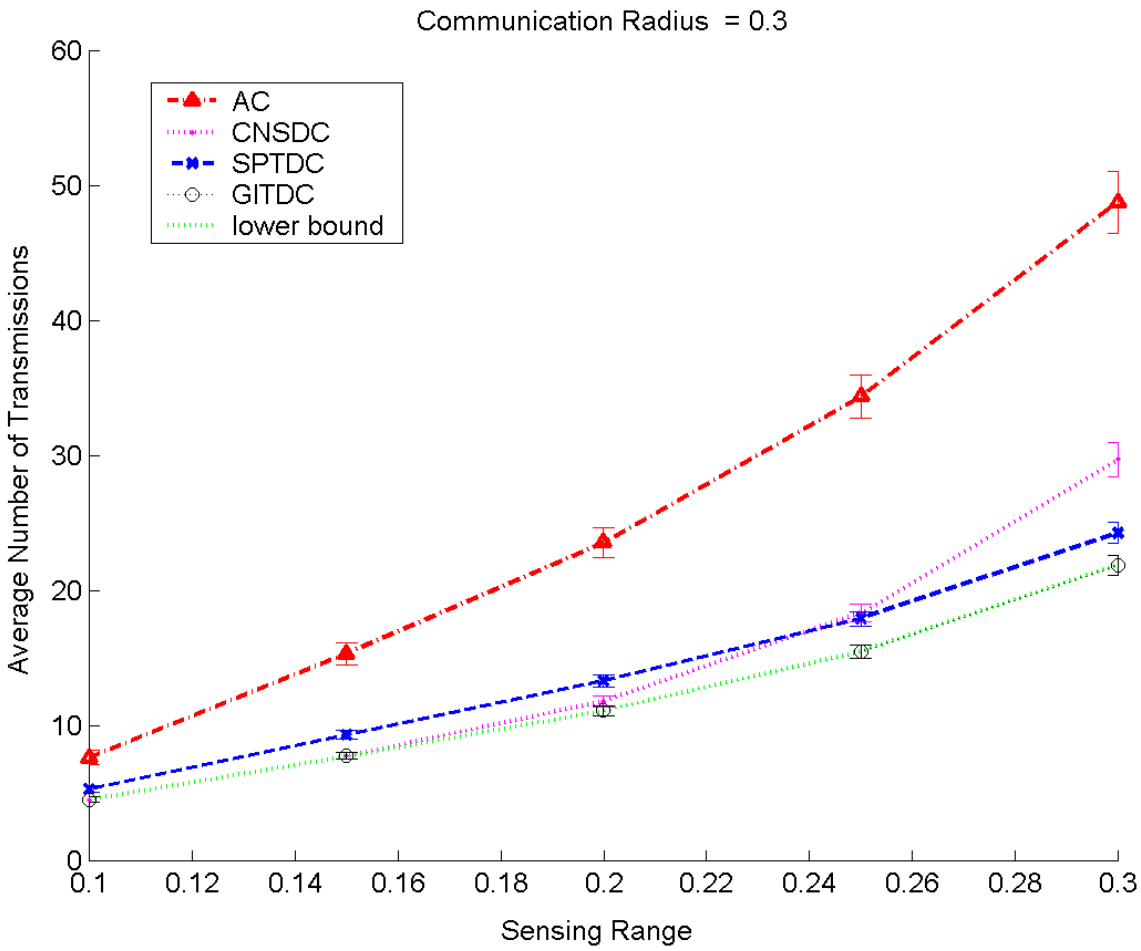
- If we have k sources, i^{th} source at distance d_i hops from sink, and diameter X for the sources:

$$((k-1)X+\min(d_i))/\Sigma d_i \leq \eta \leq (\min(d_i) + k - 1)/\Sigma d_i$$

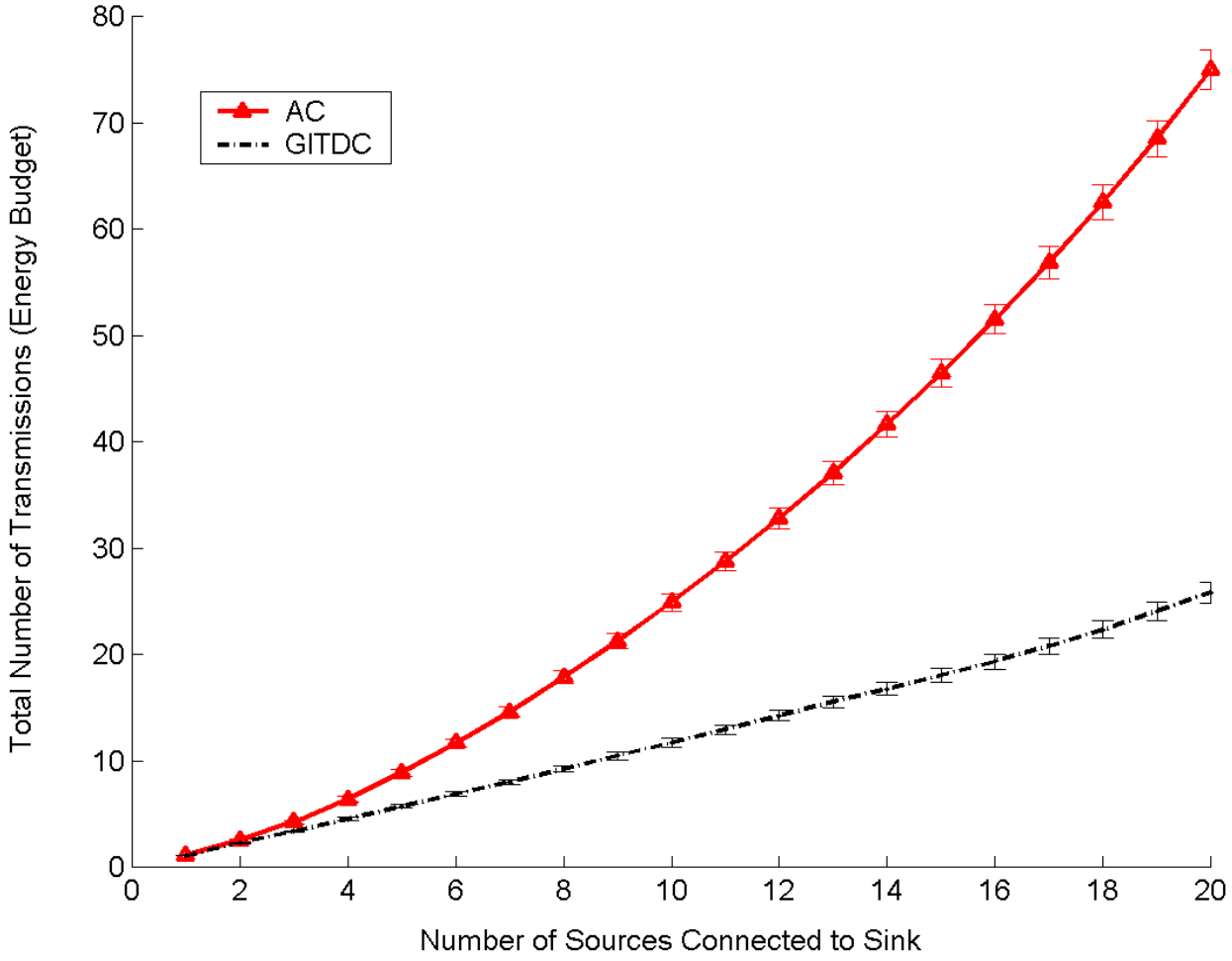
$$\lim_{d\to\infty} \eta = 1/k$$

- If the subgraph induced by the set of sources is connected, then the optimal aggregation tree can be formed in polynomial time.

Energy Savings Due to Data Aggregation



Robustness with Data-Aggregation



Advanced Aggregation Techniques

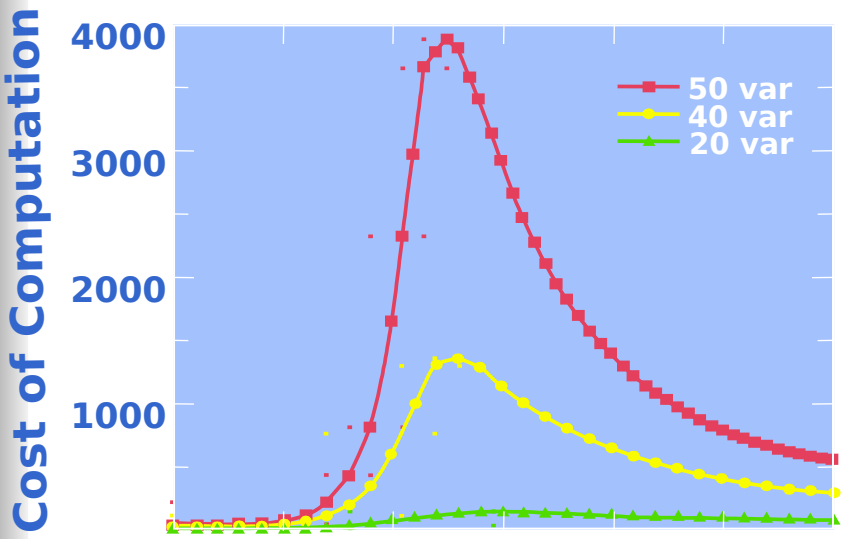
- Interests can be expressions in first order logic – interest now takes the form of question: Is this true about the world/battlefield/area?
- Individual terms in conjunctive normal form now become focus for aggregation.
  - Pushes computation further out into network
  - Naturally balances computation load in energy-limited sensor network
- Interests can also be expressed as continuous-valued random variables.
  - Aggregation performed through belief propagation
  - Minimizes number of transmissions required to update local marginal distributions.

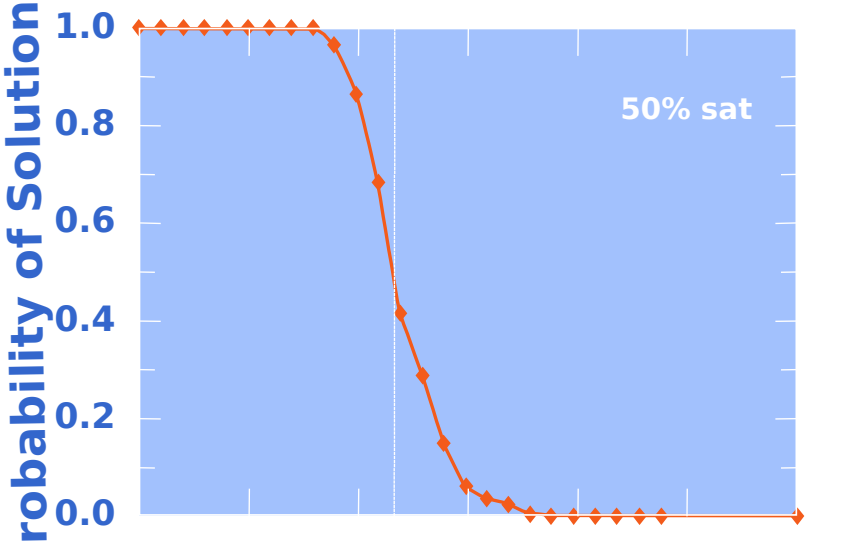
Simulation Testbed and Future Effort

- OPNET simulation testbed for directed diffusion completed for case of static nodes.
- Future emphasis on modeling mobility.
- Analytic and simulation results from new interest definitions to be presented at the next PI meeting.

Bounded Complexity

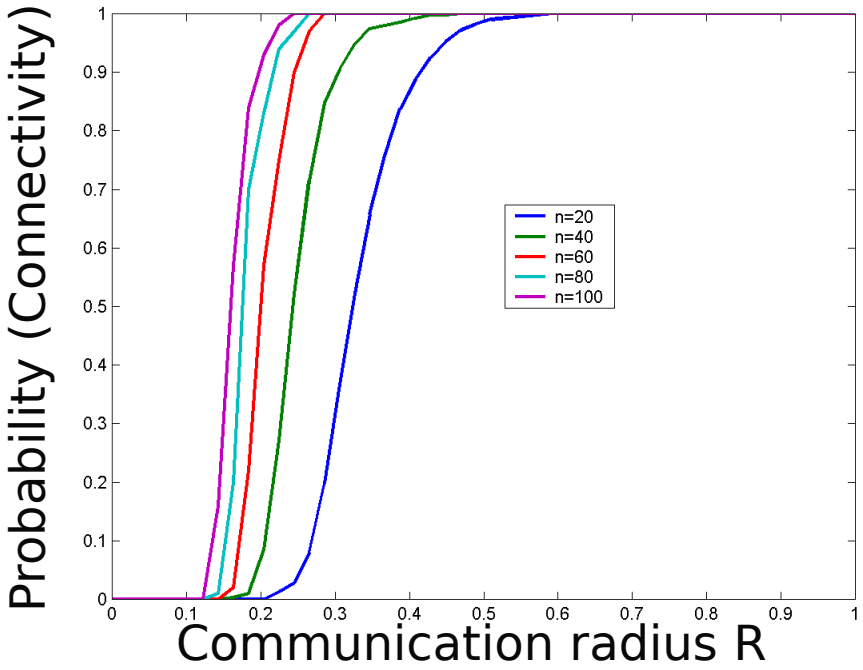
- Critical density thresholds found for many wireless network properties and for distributed constraint satisfaction problems.
  - “Phase Transitions in Wireless Networks” - Krishnamachari, Wicker and Bejar (GlobeCom’01)
  - “Distributed Problem Solving and the Boundaries of Self-Configuration in Wireless Networks” - Krishnamachari, Bejar, and Wicker (HICSS ‘02)





Phase Transition for Connectivity

- Random Graph Model: n nodes randomly located in a unit area, varying communication range R.
- Density ~ $\pi R^2 n$.
- Connectivity threshold function with O(log n) density, proved by Gupta & Kumar (1998).

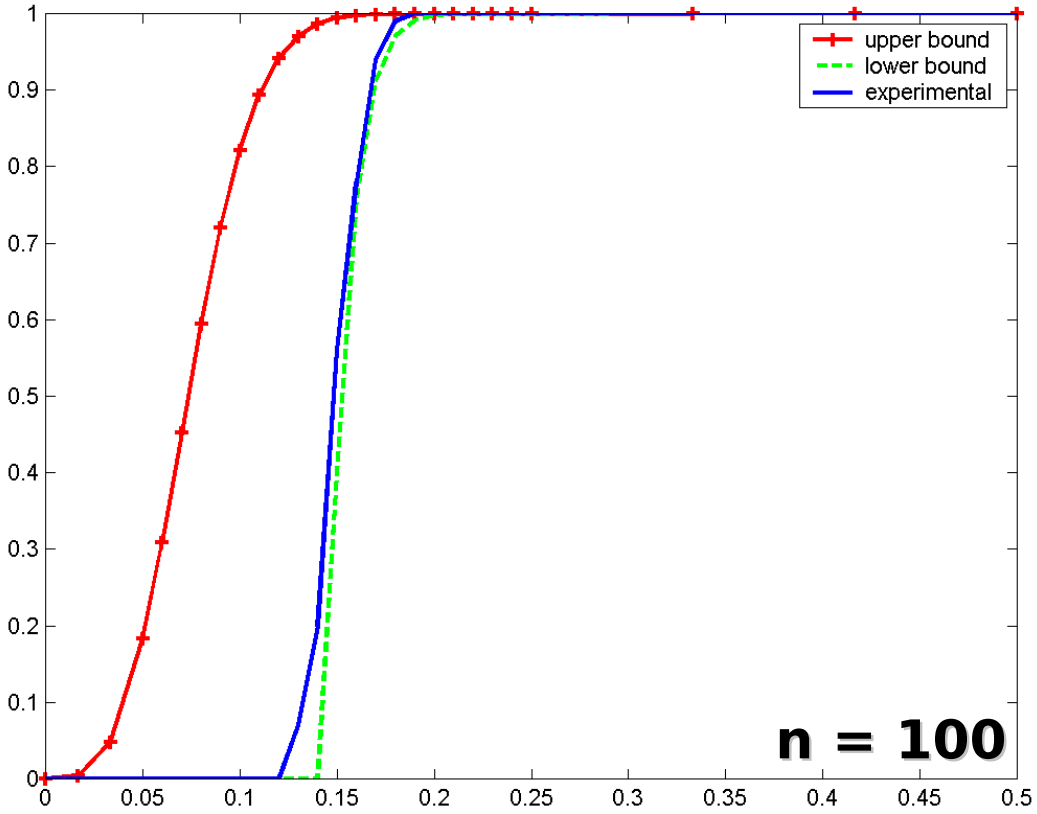


Analytical results on phase transitions

- Transition effects on Bernoulli random graphs well studied analytically by mathematicians.
- Fixed-radius random graphs that model wireless networks do not have the same independence properties - making analysis much harder.
- Finding bounds is somewhat easier.

Phase Transition Bounds

- Probability that all nodes have at least 2 neighbors



Communication radius R

Analytical Bounds for Neighbor Count

- Property: All nodes have at least k neighbors
- Let A_i = event that node i has at least k neighbors.
- Bounds:

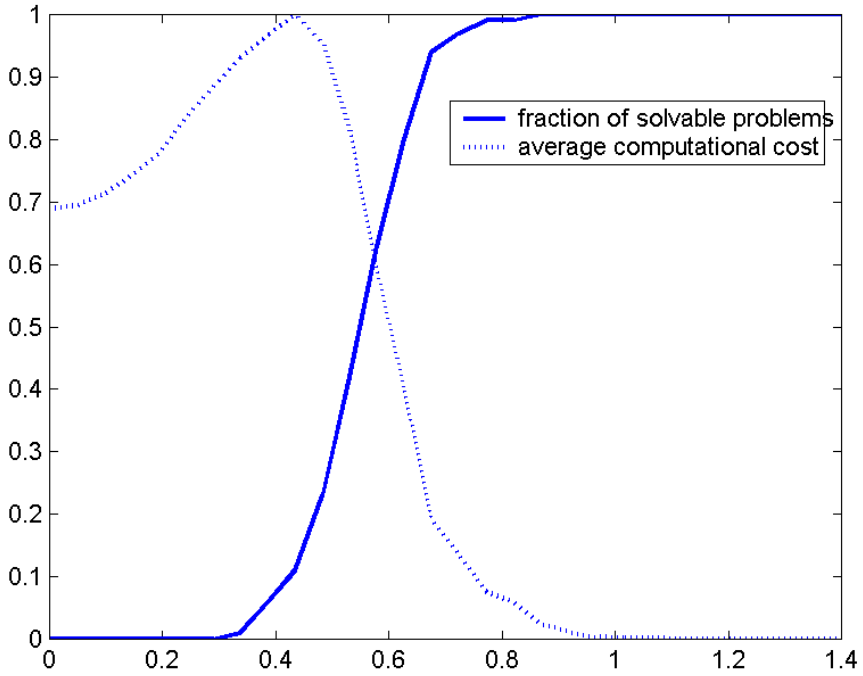
$$1 - Pr(A_i^c) \geq Pr(\bigcap_{i=1}^{n} A_i) \geq 1 - nPr(A_i^c)$$

where (for $R < 0.5$, ignoring edge effects)

$$Pr(A_i^c) = \sum_{j=0}^{k-1} \binom{n-1}{j} (\pi R^2)^j (1 - \pi R^2)^{n-1-j}$$

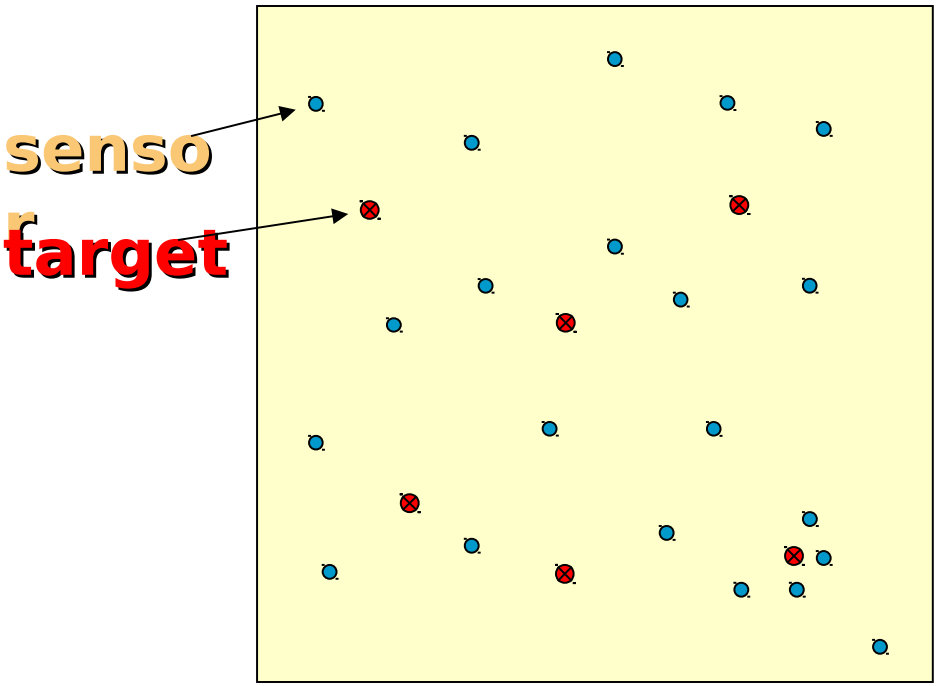
Hamiltonian Cycle Formation

- A self-configuration task useful as precursor to many efficient distributed algorithms
- NP-complete in the worst case, but easy on average beyond O(n log n) critical density threshold.



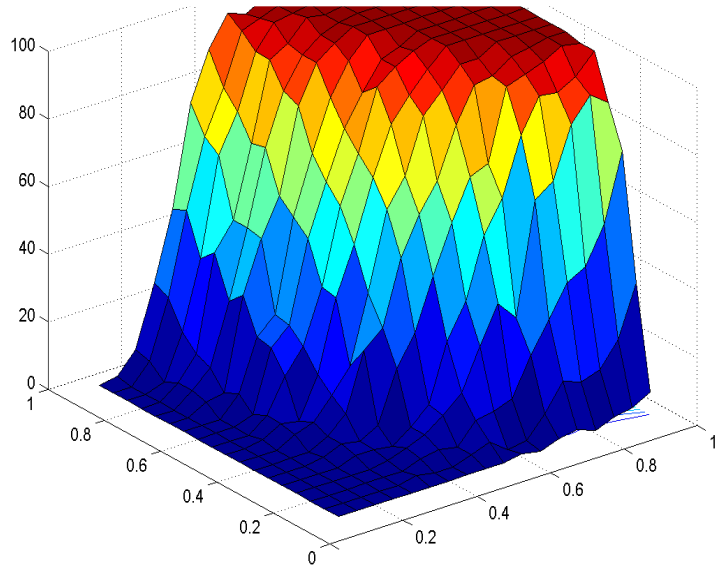
Coordinated Sensor Tracking

- Multiple sensors and targets
- Sensors communicate and sense locally
- Need 3 communicating sensors to track each target



Coordinated Sensor Tracking

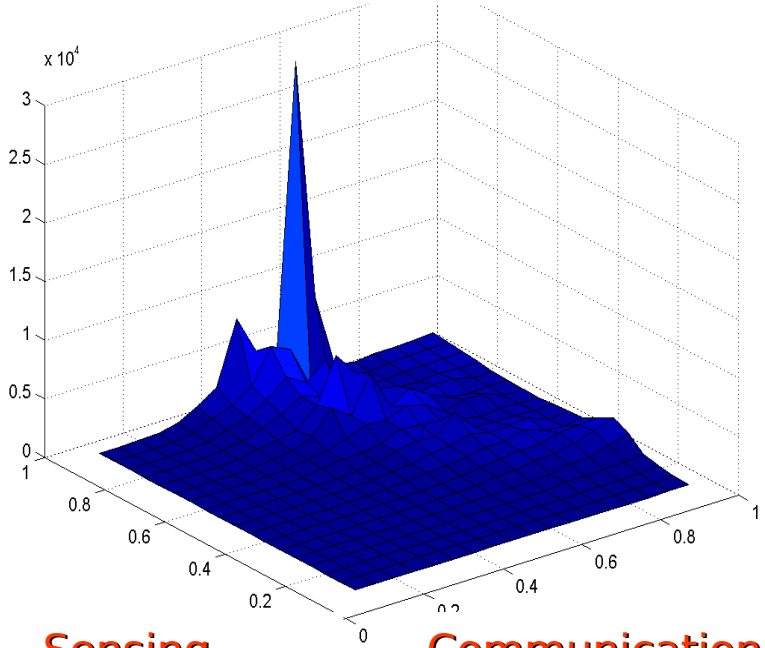
Probability of Tracking



Sensing Range

Communication Range

Mean Computation Cost

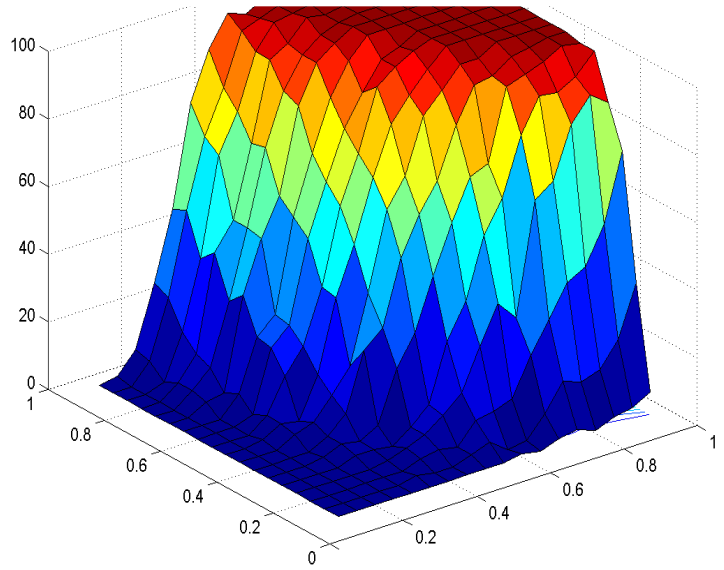


Sensing Range

Communication Range

Coordinated Sensor Tracking

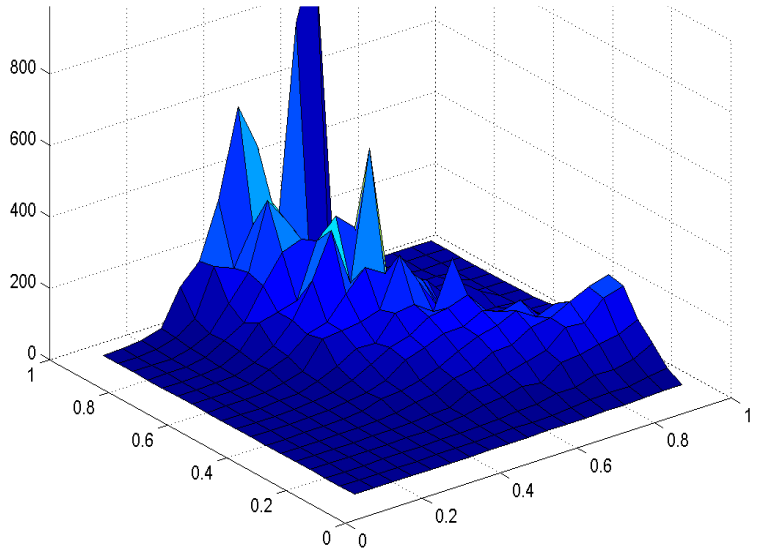
Probability of Tracking



Sensing Range

Communication Range

Mean Communication Cost



Sensing Range

Communication Range

Usefulness of Phase Transition Perspective

- Helps determine range of feasible densities for various network properties
- Can be computed offline or incorporated into online self-configuration mechanisms.
- Helps bound the computational/communication complexity of distributed algorithms.

End